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Measurement of $K^+ \to \pi^0 \mu^+ \nu \gamma$ decay using stopped kaons

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Abstract

The $K^+ \to \pi^0 \mu^+ \nu \gamma$ ($K_{\mu 3\gamma}$) decay has been measured with stopped positive kaons at the KEK 12 GeV proton synchrotron. A $K_{\mu 3\gamma}$ sample containing 125 events was obtained. The partial branching ratio $Br(K_{\mu 3\gamma}, E_\gamma > 30$ MeV$, \theta_{\mu^+\gamma} > 20^\circ)$ was found to be $[2.4 \pm 0.5(stat) \pm 0.6(syst)] \times 10^{-5}$, which is in good agreement with theoretical predictions.

Key words: Kaon decays
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Semi-leptonic radiative decays of K-mesons, $K \to \pi l \nu \gamma$ ($K_{l3\gamma}$), offer a good testing ground of hadron structure models making use of low-energy effective Lagrangians inspired by chiral perturbation theory (ChPT). It is expected that branching ratio measurements and decay spectra with a single pion in the final state provide simple but good constraints on the models. The radiative decays of mesons usually consist of an internal bremsstrahlung (IB) process and a hadron-structure-dependent direct emission (DE) process. While the IB process is dominant in the decays with electrons in the final state such as $K \to \pi e \nu \gamma$ ($K_{e3\gamma}$) decays, one expects a significant DE contribution when there is a muon in the final state, $K \to \pi \mu \nu \gamma$ ($K_{\mu 3\gamma}$), because of the larger lepton mass. The relative size of the DE effects can be calculated in strong interaction models. Following the early estimates [1,2,3], based on current algebra, calculations in the framework of the ChPT theory have been done [4].

$K_{l3\gamma}$ branching ratios of neutral kaons with electrons and muons in the final state have been reported in the literature with branching fractions of $K^0_{e3\gamma}$ and $K^0_{\mu 3\gamma}$ of 3.5×10^{-3} and 5.5×10^{-4}, respectively [5]. For the charged kaons, a $K^+_{e3\gamma}$ decay branching ratio of 2.65×10^{-4} has been measured [5], and results of the first measurement of the $K^-_{\mu 3\gamma}$ decay using an in-flight K^- beam has recently been reported [6]. In this paper, we present a new measurement of the $K^+ \to \pi^0 \mu^+ \nu \gamma$ ($K^+_{\mu 3\gamma}$) decay using a stopped K^+ beam along with detailed Monte Carlo simulations, which enabled us to determine the $K^+_{\mu 3\gamma}$ branching ratio.

The experiment was performed at the KEK 12-GeV proton synchrotron. The detector was basically the E246 setup [7], which had the 12-sector toroidal spectrometer and the ancillary detector assemblies such as the photon calorimeter and the particle tracking system. Since the system was built primarily for the purpose of a high precision test of time reversal invariance in the $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) decay [7], an elaborate simulation program based on GEANT3 [8] has been developed. Details of the setup are well documented in Ref. [9]. In addition to the T-violation search, spectroscopic studies for various decay channels have also been successfully performed using the same detector system [10,11,12].

A separated 660-MeV/c K^+ beam was stopped in an active target system. The $K_{\mu 3\gamma}$ events were identified by analyzing the μ^+ momentum with the spectrometer and detecting three photons in the CsI(Tl) calorimeter. The momentum vectors of the charged particles were determined by reconstructing their trajectories in the spectrometer using multi-wire proportional chambers (MWPCs).

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The μ^+s were selected by determining the squared mass (M^2_{TOF}) from a time-of-flight measurement. The photon energy and hit position were obtained, respectively, by summing the energy deposits and taking the energy-weighted centroid of the CsI(Tl) crystals sharing a shower. The analysis procedures of the present work for the charged particle tracking, TOF measurement, and photon energy and hit position determinations are the same as those of the previous $K_{\pi 2\gamma}$ study (see Ref. [11] for details).

Specific cuts for the $K_{\mu 3\gamma}$ selection are described below. The charged particle momentum corrected for the energy loss in the target (P_{μ^+}) was imposed to be $P_{\mu^+} < 170$ MeV/c. Events from π^+ decays in-flight and scattering of the charged particle from the magnet pole faces were eliminated by requiring the particle track to be consistent with the hit position in the ring counters surrounding the active target system [9]. The selection criterion for muons was $8000 < M^2_{\mathrm{TOF}} < 14500$ MeV$^2/c^4$, as shown in Fig. 1. Events with three photon clusters in the calorimeter were selected: two as coming from $\pi^0 \to \gamma_1\gamma_2$ and one being a radiative photon (γ_3). Since there are three possible combinations to form a π^0 from three photons, a quantity Q^2 was introduced to find the correct pairing,

$$Q^2 = (M_{\pi^0} - M)^2/\sigma_M^2 + (\cos\theta^{\mathrm{MEA}}_{\mu^+\gamma_3} - \cos\theta^{\mathrm{CAL}}_{\mu^+\gamma_3} - \alpha)^2/\sigma_\alpha^2, \tag{1}$$

where M_{π^0} is the invariant mass of the selected pair and $\theta_{\mu^+\gamma 3}$ is the opening angle between the μ^+ and γ_3. The superscripts MEA and CAL stand for the measured angle and the angle calculated from other observables by assuming the $K_{\mu 3\gamma}$ kinematics. The pair with the minimum Q^2 ($=Q^2_{\mathrm{min}}$) among the three possible combinations was adopted as the correct pairing. The σ (σ_M, σ_α) and offset values (M, α) in each terms are $\sigma_M = 10.92$ MeV/c^2, $\sigma_\alpha = 0.273$, $M = 118.3$ MeV/c^2, and $\alpha = 0.265$. The choice of the parameters were determined to obtain the highest probability for the correct pairing by using the simulation data. The correct pairing probability was estimated to be 69% from the Monte Carlo simulation. Further, since most of background events do not satisfy the $K_{\mu 3\gamma}$ kinematics, the cut of $Q^2_{\mathrm{min}} < 1.5$ reduced the background contaminations. An additional cut condition, $\cos[\theta_{\gamma\gamma}]_{\mathrm{min}} < 0.45$, was applied to reject events with a photon split into multiple clusters, where $[\theta_{\gamma\gamma}]_{\mathrm{min}}$ is the minimum opening angle of photons among the three combinations. The above conditions were sufficient to select $K_{\mu 3\gamma}$ events. From this analysis, a sample with 565 events was extracted. The spectra are shown in Fig. 2. The black(solid) histograms are the data comprising of the $K_{\mu 3\gamma}$ events and the background events to be discussed below.

There are three major background components, $K^+ \to \pi^+\pi^0\pi^0$ ($K_{\pi 3}$), $K^+ \to \pi^+\pi^0\gamma$ ($K_{\pi 2\gamma}$), and $K_{\mu 3}$. The former two could imitate $K_{\mu 3\gamma}$ if the pion decays in flight and the three photons hit the calorimeter. Also, $K_{\mu 3}$ with an accidental photon could contribute to $K_{\mu 3\gamma}$. The $K_{\pi 3}$ and $K_{\pi 2\gamma}$ contaminations were

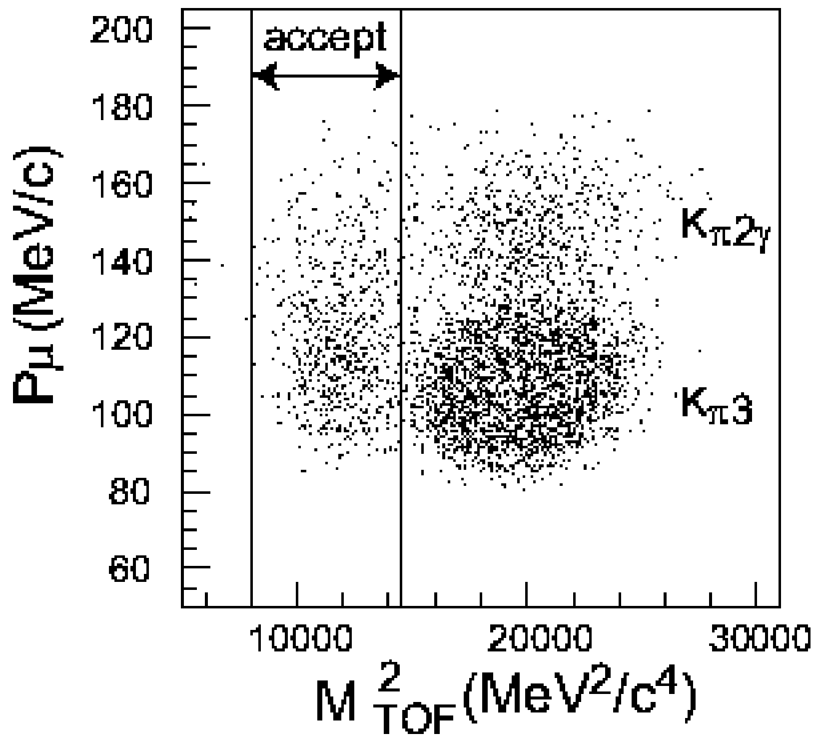

Fig. 1. Correlation plot of M^2_{TOF} and P_μ. The $K_{\pi3}$ and $K_{\pi2\gamma}$ events which were used to calculate the $K_{\mu3\gamma}$ branching ratio and the background fractions are also seen.

estimated using a Monte Carlo simulation. The simulation data were analyzed in the same manner as the experimental data, yielding surviving background fractions. In order to determine these fractions, the results of careful evaluations, carried out in the previous $K_{\pi2\gamma}$ study [11], were used. These $K_{\pi3}$ and $K_{\pi2\gamma}$ events can be seen in the P_μ-M^2_{TOF} scatter plot in Fig. 1. The numbers of the $K_{\pi3}$ and $K_{\pi2\gamma}$ events were calculated from those of the experimental $K_{\pi3}$ and $K_{\pi2\gamma}$ events by using acceptance ratios as,

$$Y(K^{BG}_{\pi3}) = \frac{\Omega(K^{BG}_{\pi3})}{\Omega(K^{NM}_{\pi3})} \cdot Y(K^{NM}_{\pi3}), \tag{2a}$$

$$Y(K^{BG}_{\pi2\gamma}) = \frac{\Omega(K^{BG}_{\pi2\gamma})}{\Omega(K^{NM}_{\pi2\gamma})} \cdot Y(K^{NM}_{\pi2\gamma}), \tag{2b}$$

where $Y(X)$ is the yield of decay channel X and $\Omega(X)$ is the detector acceptance determined by the simulation. BG and NM stand for the selection conditions of the present background evaluation and the previous normal $K_{\pi2\gamma}$ study [11], respectively. Potential systematic errors from the uncertainty of the calculated acceptances can be reduced by taking the ratio of the acceptances. Substituting the geometrical acceptance of our setup, $\Omega(K^{BG}_{\pi3}) = 9.91 \times 10^{-7}$, $\Omega(K^{NM}_{\pi3}) = 9.45 \times 10^{-5}$, $\Omega(K^{BG}_{\pi2\gamma})$=$3.61 \times 10^{-6}$, and $\Omega(K^{NM}_{\pi2\gamma}) = 2.40 \times 10^{-4}$ and the measured yields $Y(K^{NM}_{\pi3})$=32105 and $Y(K^{NM}_{\pi2\gamma}) = 4434$, $Y(K^{BG}_{\pi3})$ and $Y(K^{BG}_{\pi2\gamma})$ were determined to be 337 and 67, respectively, corresponding to 60%

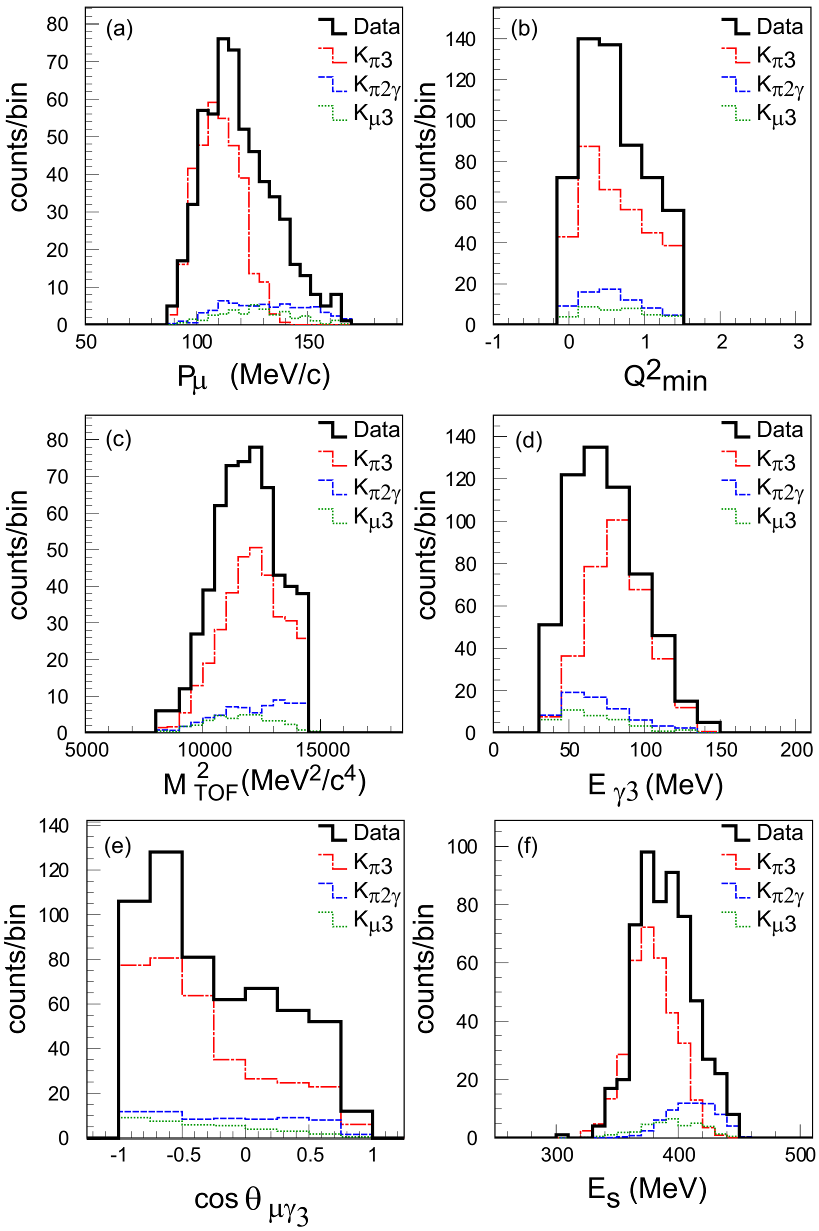

Fig. 2. Black(solid) histograms are experimental data extracted with the present selection conditions for (a) P_{μ^+}, (b) Q^2, (c)M^2_{TOF}, (d) $E_{\gamma 3}$, (e) cos$\theta_{\mu^+\gamma 3}$, and (f) E_s. Red(dot-dashed), blue(dashed), and green(dot) histograms are backgrounds due to $K_{\pi 3}$, $K_{\pi 2\gamma}$, and $K_{\mu 3}$ decays, respectively.

and 12% of the total events. The contribution from $K_{\mu 3}$ was studied by accepting accidental events in the CsI(Tl) TDC data and its number was found to be 36. The background spectra are shown in Fig 2 as the red(dot-dashed), blue(dashed), and green(dot) histograms for $K_{\pi 3}$, $K_{\pi 2\gamma}$, and $K_{\mu 3}$, respectively. Fig. 3 shows the background-subtracted distributions compared with the simulation described in the following. The number of $K_{\mu 3\gamma}$ events was found to be 125 ± 25.

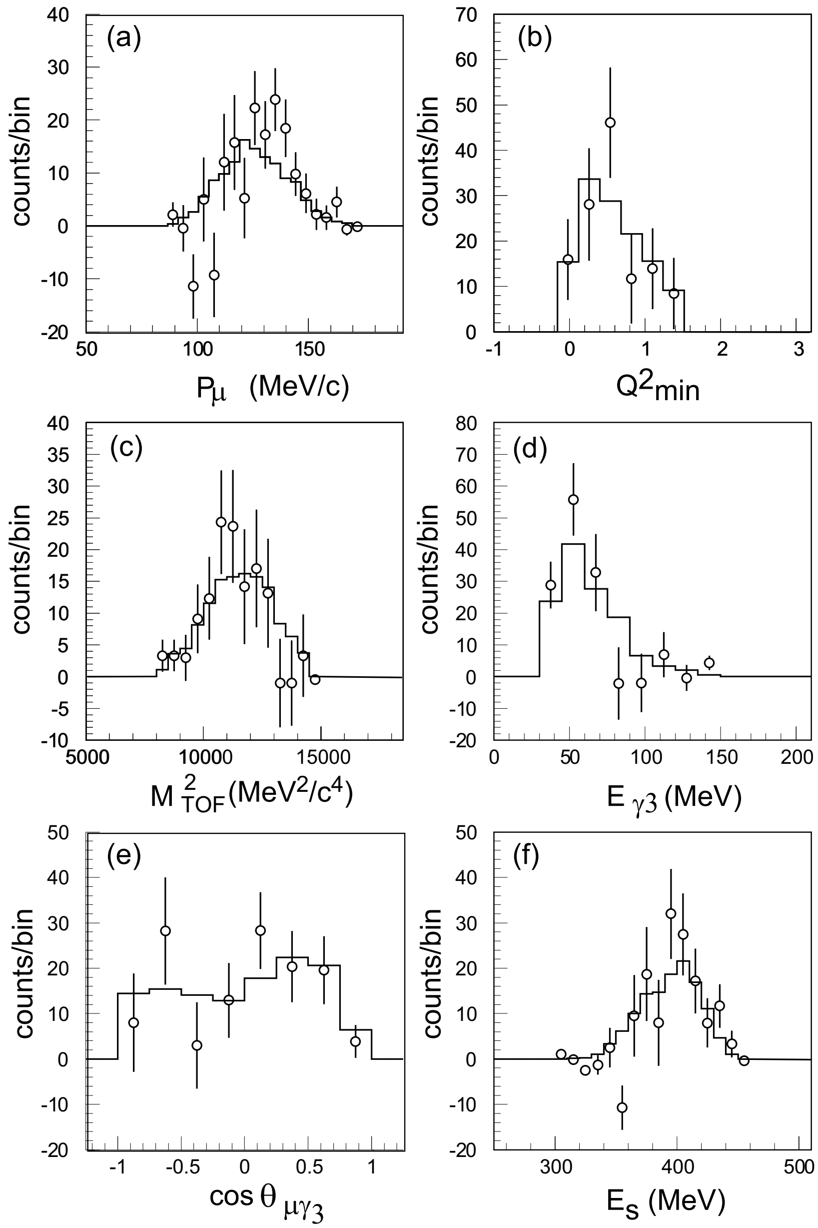

Fig. 3. $K_{\mu 3\gamma}$ spectra obtained by subtracting backgrounds (dots): (a) P_{μ^+}, (b) Q^2, (c)M^2_{TOF}, (d) $E_{\gamma 3}$, (e) cos$\theta_{\mu^+\gamma 3}$, and (f) E_s. The histograms are the Monte Carlo simulations.

In the simulation, the $K_{\mu 3\gamma}$ data were generated according to the matrix elements given in Ref. [1]. Here, only the IB process was taken into account because the present result is not sensitive enough to study the DE contribution (see below). The detector acceptance for $K_{\mu 3\gamma}$ in the region of $E_{\gamma_3} > 30$ MeV, $\theta_{\mu^+\gamma_3} > 20°$ was determined to be $\Omega(K_{\mu 3\gamma}) = 1.52 \times 10^{-4}$. The reduced χ^2 values of fits between the experimental data and the simulation are (a)1.33, (b)1.09, (c)0.80, (d)1.24, (e)0.94, and (f)1.05 in each spectrum, lending credence to our claim that these are indeed $K_{\mu 3\gamma}$ events.

The partial branching ratio of $K_{\mu 3\gamma}$ in the region of $E_{\gamma_3} > 30$ MeV, $\theta_{\mu^+\gamma_3} > 20^\circ$ can be derived from separately comparing with the $K_{\pi 2\gamma}$ and $K_{\pi 3}$ branching ratio by means of the yield and acceptance ratios as,

$$Br(K_{\mu 3\gamma}) = \frac{Y(K_{\mu 3\gamma})}{Y(K_{\pi 2\gamma}^{NM})} \frac{\Omega(K_{\pi 2\gamma}^{NM})}{\Omega(K_{\mu 3\gamma})} \cdot Br(K_{\pi 2\gamma}), \tag{3a}$$

$$Br(K_{\mu 3\gamma}) = \frac{Y(K_{\mu 3\gamma})}{Y(K_{\pi 3}^{NM})} \frac{\Omega(K_{\pi 3}^{NM})}{\Omega(K_{\mu 3\gamma})} \cdot Br(K_{\pi 3}), \tag{3b}$$

where $Br(X)$ is the branching ratio for the process X. Making use of $Br(K_{\pi 2\gamma}) = 2.61 \times 10^{-4}$ predicted by theoretical calculation [13] and $Br(K_{\pi 3}) = 1.73 \times 10^{-2}$ by the Particle Data Group [5], the $K_{\mu 3\gamma}$ branching ratio was determined to be $Br(K_{\mu 3\gamma}) = (2.4 \pm 0.5) \times 10^{-5}$ from $K_{\pi 2\gamma}$ and $Br(K_{\mu 3\gamma}) = (2.8 \pm 0.6) \times 10^{-5}$ from $K_{\pi 3}$, which are consistent with each other. Since only π^+s in the end-point region of the $K_{\pi 3}$ decays were accepted by the toroidal spectrometer and the spectrometer acceptance was strongly affected by the $K_{\pi 3}$ form factors assumed in the simulation, we adopted $Br(K_{\mu 3\gamma})$ from Eq.(3a) and used Eq.(3b) only for a consistency check of the deduced results.

The major systematic errors in the determination of the $K_{\mu 3\gamma}$ branching ratio come from uncertainty of the $K_{\pi 3}$ and $K_{\pi 2\gamma}$ background fractions. Since we rely on the Monte Carlo simulation for the background estimation, imperfect reproducibility of the experimental conditions introduces systematic errors. We carefully evaluated the effects from the TOF measurement and the charged particle tracking, which would distort the $K_{\mu 3\gamma}$, $K_{\pi 3}$, $K_{\pi 2\gamma}$ spectra and, as a consequence, introduce the systematic errors. These errors were estimated by varying the inputs of the TOF resolution and the MWPC spatial resolution in the simulation within their maximum likely uncertainties (see below). In order to estimate the other systematic effects, the $K_{\pi 3}$ and $K_{\pi 2\gamma}$ fractions could be controlled by requiring an extra cut at the cost of good $K_{\mu 3\gamma}$ events as follows.

Since events with π^+ decays in the spectrometer (DIS) are seen as a tail under the π^+ peak, as shown in Fig. 2(c), a wrong estimate of the TOF resolution could introduce a systematic error. This effect was estimated by changing the TOF resolution assumed in the simulation from $\sigma_{\mathrm{TOF}} = 270$ ps, which was experimentally determined using the K_{e3} and $K_{\mu 3}$ decays, to $\sigma_{\mathrm{TOF}} = 270 \pm 20$ ps. Its contribution to the branching ratio error was found to be $\Delta Br(K_{\mu 3\gamma}) = 0.1 \times 10^{-5}$. Also, the muon mass cut point dependence was investigated to study its contribution to the DIS component and found to be very small. We note that an asymmetric structure due to the DIS contribution shown in Fig. 2(c) was removed by subtracting the $K_{\pi 3}$ and $K_{\pi 2\gamma}$ backgrounds.

Since most of DIS events were rejected by the consistency cut between the hit position in the ring counter and the charged particle track, the MWPC

spatial resolution for the input to the simulation affects the estimation of the background fraction. In the simulation, we varied the resolutions by $\pm 10\%$ from the experimental values to estimate this effect. The background fraction was obtained by repeating the same analysis. We arrived at $\Delta Br(K_{\mu 3\gamma}) = 0.2 \times 10^{-5}$ as the contribution to systematic error from particle tracking.

The background contribution is also influenced by the total energy sum of the μ^+ and the photons defined as $E_s = E_{\mu^+} + \sum_{i=1}^{3} E_{\gamma i}$ because the E_s distribution has a specific structure corresponding to the decay channel, as shown in Fig. 2(f). Selecting events with the conditions of $E_s > 400$ MeV and $E_s < 400$ MeV, the $K_{\mu 3\gamma}$ branching ratio was determined to be $(2.9 \pm 0.6) \times 10^{-5}$ and $(2.0 \pm 0.7) \times 10^{-5}$, respectively. The background fractions using these cut conditions are summarized in Table 1. It is noted that the E_s variation affects the background contributions significantly but does not change the $K_{\mu 3\gamma}$ branching ratio which depends on the ratio of events and acceptances. This feature indicates the correct estimation of the $K_{\pi 3}$ and $K_{\pi 2\gamma}$ background fractions and the detector acceptances. Although these parameters are consistent within errors, the parameter shifts, $\Delta Br(K_{\mu 3\gamma}) = 0.5 \times 10^{-5}$, were treated as a systematic error due to an acceptance uncertainty for the background events.

The γ mispairing effect was studied by varying the pairing probability. In addition to the standard $K_{\mu 3\gamma}$ selection conditions, an extra cut, $\cos\theta_{\gamma 1\gamma 2} > -0.5$, was imposed, where $\theta_{\gamma_1\gamma_2}$ is opening angle between γ_1 and γ_2, and the pairing probability became 81% with a loss of good $K_{\mu 3\gamma}$ events,. The $Br(K_{\mu 3\gamma})$ was found to be consistent within 0.2×10^{-5} which was regarded as the systematic error. The statistical fluctuation of the backgrounds from $K_{\mu 3}$ with an accidental photon was treated as a systematic error of 0.05×10^{-5}. The total systematic error was evaluated by adding all these contributions in quadrature, as shown in Table 2. The most dominant effect is due to the error of the background fractions from the uncertainty of the detector acceptance.

In conclusion, we have performed a measurement of the radiative $K_{\mu 3\gamma}$ decay using stopped positive kaons. The data sample of 125 events was obtained by subtracting the $K_{\pi 3}$, $K_{\pi 2\gamma}$, and $K_{\mu 3}$ backgrounds. The final result for the branching ratio is $Br(K_{\mu 3\gamma}, E_{\gamma_3} > 30\text{MeV}, \theta_{\mu^+\gamma_3} > 20^\circ) = [2.4 \pm 0.5(stat) \pm 0.6(syst)] \times 10^{-5}$, by normalizing to the theoretical value of internal bremsstrahlung in the $K_{\pi 2\gamma}$ decay. This result is in agreement with the prediction from chiral perturbation theory [4]: $Br(K_{\mu 3\gamma}, E_{\gamma_3} > 30\text{MeV}, \theta_{\mu\gamma_3} > 20^\circ) = 2.0 \times 10^{-5}$. The current experimental result is not yet sensitive enough to study the contribution from hadron structure effects, which is predicted to be at the level of a few % of the rate [4], and/or to search for T-violating triple correlations such as $P_T = \vec{p_\gamma} \cdot (\vec{p_\mu} \times \vec{p_{\pi^0}})$ [1,14]. It is conceivable that such experiments may be attempted at the new J-PARC facility currently under construction [15].

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Table 1
Variation of the $K_{\pi 3}$ and $K_{\pi 2\gamma}$ background fractions with the E_s cuts. The $Y(K_{\mu 3\gamma})$ and $Br(K_{\mu 3\gamma})$ values are also shown.

E_s(MeV)	$K_{\pi 3}$	$K_{\pi 2\gamma}$	$Y(K_{\mu 3\gamma})$	$Br(K_{\mu 3\gamma})\times 10^5$
no cut	60%	12%	125	2.4 ± 0.5
$E_s > 400$	28%	27%	68	2.9 ± 0.6
$E_s < 400$	74%	5%	57	2.0 ± 0.7

Table 2
Summary of major systematic errors. All items are added in quadrature to get the total.

Error source	Uncertainty of $Br(K_{\mu 3\gamma})$ $\times 10^5$
TOF resolution	0.1
MWPC resolution	0.2
Detector acceptance	0.5
γ mispairing	0.2
Accidental background	0.05
Total systematic error	0.6